Practical Considerations & Good Protocol for the Interpretation of Ultramafic & Mafic Rock Physical Property Data

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SUMMARY

An increase in the availability of inexpensive and easy-to-use geophysical tools has led to an interest in the development of larger rock physical databases. These data are often interpreted at face value, with little consideration given to the selection of representative samples, sample preparation, or even the practical limitations of measuring tool. Consequently, wide-ranging data are often observed. This may lead to incorrect interpretation. Magnetic susceptibility and density measurements are now routinely made on drill-core specimens. These data are often amalgamated with historical measurements in an effort to make localised physical property databases more robust. Two practical considerations regarding these data are discussed: 1) The evaluation of dry bulk density data, and inherent issues with measuring dimensions or applying volume assumptions; 2) The appropriateness of using commonly employed inductive electromagnetic tools, i.e. handheld magnetic susceptibility meters, to resolve induced magnetisation.

Changes in core-diameter due to coring and rock swelling are studied, as are the effects of core volume loss due to cutting. A comparison between empirical measurements and volume estimations has shown that up to 7% and 30% of variability may be attributed to changes in drill-core diameter and split-core geometry, respectively. Dry bulk density data that have been calculated using estimated volumes may be in extreme error and therefore inappropriate to use. Orientation markings or bottom-of-hole lines have shown to correlate with reduction in variability of core volume loss caused by cutting. The use of an Almonte core-holder, or similar, is shown to produce an even lower and less variable core volume loss. The reliability of historical dry bulk density values may be ranked based on the presence of orientation or bottom-of-hole line, or known implementation of a core cutting holders.

Bulk magnetic susceptibility measurements made on ultramafic and mafic diamond drill-core using a handheld instrument are evaluated. Comparisons with Qmeter magnetisation data show that handheld bulk magnetic susceptibility values may be in the error of several orders of magnitude. Anisotropy is hypothesised to be the principal cause of variation. Furthermore, conductivity effects that are induced by handheld meters, e.g. frequency dependence, may contribute to an under-reporting of values.

Key words: Petrophysics; ultramafic; mafic; magnetic susceptibility; Qmeter; dry bulk density; density

INTRODUCTION

There is a growing reliance on geophysical methods as mineral exploration moves under cover. The understanding of rock physical properties is a priori to the interpretation of geophysical data and geologically induced responses. The recognition of the importance of petrophysics has led to numerous initiatives around the world to create petrophysical databases. The need to grow more robust physical rock property databases is acknowledged. Subsequently, measurements from recent campaigns are frequently incorporated with historical data. Historical data are often the legacy of former project owners, and nearly always have very little accompanying detail as to measurement processes or sample rationale. Although not commonly practiced, bivariate plots can be used to compare petrophysical data derived from a variety of tools or measurement processes. Subsequently, the validity of historical data may be investigated, and measurement protocols evaluated. The accurate classification of data and the understanding the practical limitations of measuring tools still remains a concern.

A cautionary note on historical density data, and applying density data:
Caution must be exercised when interpreting density data described only as ‘SG’, an abbreviation for specific gravity, or more plainly labelled ‘density’. These ambiguous terms may be in reference to loss on ignition thermo-gravimetry studies (i.e. data derived from pulverised material which is then heated, and is usually undertaken during whole rock geochemical studies), dry bulk density (i.e. density data that accounts for open or air-filled pore spaces), wet bulk density (i.e. density data that accounts for saturated or fluid-filled pore spaces), or grain density (i.e. density data that accounts for mineral constituents, no porosity). The three later densities are used in geophysical inversion and resource modelling. Emerson (1990) and Lipton & Horton (2014) provide detailed background on density principles, collection methodologies, and best practices.

Dry bulk density measurements are quick and relatively simple to make, and are therefore most abundant within historical petrophysical databases. Dry bulk density measurements are calculated by dividing the dry-mass of a sample by volume. Volume is regularly calculated as the product of the measured length of trimmed drill core, i.e. perpendicular ends, and the area of the end of the drill-core specimen. The area of the ends of drill-core is nearly always assumed to be consistent across the respective specimen length. Often volumes are approximations, with core diameters assumed to be consistent, or split core representative of half cylinders. Lipton & Horton (2014) and Scogings et al. (2015) summarise the importance of correctly measuring the dimensions of trimmed diamond drill core samples, and recognise that split core is seldom half a cylinder. Scogings et al. (2015) also note that approximately 6% of HQ split core volume, and 8% of NQ split core volume, is lost when a 3mm cutting blade is used along the centreline of the core. Volume may vary considerably if an inconsistent diameter and imperfect split of diamond drill-core are not fully considered (Figure 1). While it is possible to measure dry bulk density accurately via Archimedes' principle (Emerson, 1990), the requirement of measuring a dry mass, submerged mass and saturated mass is often deemed cumbersome and time consuming.

Grain density, often called 'wet density' due to employment of Archimedes' principle, is favoured within modern- industry practices, largely due to the absent requirement of directly measuring volume. However, care must be taken to ensure that porous samples are adequately submerged and that pore spaces are saturated. This is particularly important in the case of sedimentary, weathered and fractured rocks. The porosity of ultramafic and mafic rocks is minor and frequently considered to be trivial for geophysical modelling. However, even minute changes in ultramafic and mafic rock porosity can provide a pathway for fluids and alteration processes and should therefore not be overlooked (Adams & Dentith, 2018). The use of grain density data are favoured with deep, i.e. >5km, subsurface modelling, largely due to the fact that pore spaces and fractures close with pressure at depth. In contrast, the use of wet bulk density should be considered when interpreting seismic and acoustic impedance data, or undertaking basin studies, as most rocks have a degree of fluid-saturated pore space. However, this is not always the case, and the use of dry bulk density may be more appropriate (e.g. regolith, weathered rocks). The study of porosity is therefore important when determining which type of data to use.

Understanding the tools that we use – Magnetic susceptibility meters:

The interpretation of total magnetic field data is fundamental to mapping subsurface geology, and is often used to infer structure and to target ore-related positive magnetic anomalies. As such, understanding rock magnetisation data is important. The employment of handheld magnetic susceptibility meters is common within the minerals exploration industry. Measurements are frequently made at least once on every metre mark of diamond drill-core. The importance of collecting representative data and bulk susceptibility measurements, i.e. geometric mean of many measurements (Tarling & Hrouda, 1993), is understood but often neglected.

Most handheld magnetic susceptibility meters use an inductive pickup coil and oscillator to measure induced magnetisation by detecting a current induced in the coil due to the changing magnetic moment of a sample. Strictly speaking, these magnetic susceptibility meters are an electromagnetic tool. The effects of conductivity must be considered:

- Sample half space and void problems need to be corrected. Many manufacturers offer factory 'drill-core corrections' to address these issues. However little literature exists on how these corrections are derived and as to whether an often linear approximation is appropriate for wide-ranging samples;
- Thermal instability issues should be considered and are discussed in Schmidt & Lackie (2014);
- Frequency dependence is important. The choice of instrument frequency is often overlooked despite recognition in literature (Clark, 1997; Clark, 2014). Rocks with conductive minerals, e.g. massive-sulphides, should be measured using a frequency <1kHz (Clark, 2014). Conductive minerals produce secondary eddy-currents in response to an inductive transmittance. These eddy-currents may mask the change observed in magnetic moment, thereby under-reporting magnetic susceptibility values. Most handheld magnetic susceptibility meters operate at ~10kHz, and are therefore likely to report erroneous values for conductive samples;
- Mineral fabrics, in particular that of magnetic or conductive minerals, can significantly bias handheld instrument data. The consideration of anisotropy is therefore extremely important. The calculation of bulk susceptibility values may reduce some of this bias. However, the need to physically measure parallel to drill-core surfaces (a requisite to overcome half space void issues attributed to sensor size and geometry) means that only fabrics normal to the drill core are measured. Consequently, bulk magnetic susceptibility data from hand held instruments might not be representative of anisotropic samples.

The recent creation of the Qmeter magnetisation meter now provides a means to easily measure induced and remanent magnetism (Schmidt & Lackie, 2014). Most crustal rocks have a Koenigsberger (Q) ratio >1, indicating that remanent magnetisation is at least as important as induced magnetisation. Furthermore, the Qmeter allows the acquisition of multi-axial magnetisation measurements via an isotropic assumption, thereby providing a means to evaluate the appropriateness of using handheld magnetic susceptibility meters to measure anisotropic samples (Adams & Dentith, 2017).

METHOD AND RESULTS

Evaluation of dry bulk density data, and inherent issues with volume assumptions:

The empirical dimensions of diamond drill-core from the Plutonic Well Greenstone Belt and the Eastern Goldfields are compared to synthetic dimensions that are based on assumptions of a known and consistent core barrel, and perfect half cylinder geometry for split core. Digital vernier callipers were used to measure the trimmed lengths of diamond-drill core, as well as the sagitta and chord for split core samples, and diameter for full core samples. The chord and sagitta, of split core must be measured in order to obtain the radius, (Equation 1) and area of the segment (Equation 2). Volume is the product of area of the segment and length of the drill-core:

Radius of Segment = $S/2 + (C^2/(8*S))$ (Equation 1)
Area of Segment = $R_S^2(ACos((R_S-S)/R_S)) - (R_S-S)*\sqrt{(2*R_s*S-S^2)}$ (Equation 2)
C = Chord; S = Sagitta; R_s = Radius

As shown in Figure 1, a large discrepancy may exist between assumed-volume and measured volume. Measured drill-core diameters can vary to assumed drill-core diameters by more than 7%. Volume loss is observed to be more frequent, however volume gain may occur due to rock swelling. The cutting of drill-core has the largest effect on core volume loss. The method in which drill core is cut biases data. Data where drill core has been cut using no markings or holder presents the widest range of variation. The use of orientation or bottom-of-hole lines significantly decreases this variability. The use of a core holder, e.g. Almonte v-core holder, shows little variability with regards to volume loss. Here, the majority of core volume loss is attributed to the core blade and is in good agreement with Scogings et al. (2015).

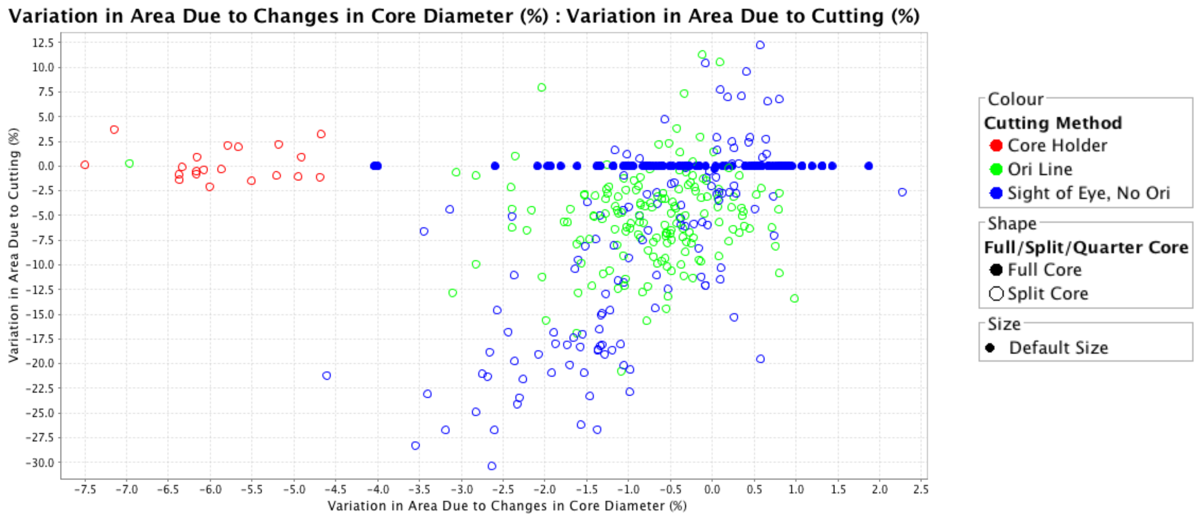

Figure 1: Variation in area due to core diameter inconsistencies vs. variation in area attributed to cutting. The variation in area equals variation in volume if a consistent sample length is applied. Data points are coloured according to cutting method. Open circles show data from split core samples, closed circles show data from full core samples.

The appropriateness of using one tool to determine magnetic response of drill-core:
Magnetic susceptibility measurements were made using a handheld instrument (Adams & Dentith, 2016). A factory half-space drill-core correction factor was applied to each measurement and a geometric mean used to calculate a bulk magnetic susceptibility value. Natural remanent magnetisation studies are ongoing and are being made using a MagneticEarth Qmeter magnetisation meter (Adams & Dentith, 2017). The Qmeter applies the methods of Breiner (1973) to measure both induced and remanent magnetism. 158 samples have presented a reliably measurable magnetic moment, thereby allowing remanent and induced magnetisation intensities to be calculated. Magnetic susceptibilities were calculated from induced magnetisation data (Clark, 2014; Adams & Dentith, 2017). Two laboratory-determined test standards (MagneticEarth, 2015) permitted checks of satisfactory reproducibility of magnetic susceptibility and remanent magnetisation intensity. Instrument accuracy was determined to be better than 9% and 5%, respectively.

Figure 2 shows a comparison of magnetic susceptibility data derived from Qmeter (Adams & Dentith, 2017) and handheld instrument instrumentation. Q-ratio and apparent porosity data (Dentith & Adams, 2018) are also shown. Four distinct populations are subsequently observed within this plot:

- Group 1: Data correlate and show that induced magnetisation is dominant, and or is isotropic to remanence. Spectral studies confirm talc Mg-rich chlorite mineralogy (Adams & Dentith, 2018);
- Group 2: Handheld instrument values correlate poorly and are up to several orders of magnitude less than Qmeter data. Variation may be caused by anisotropy. Samples are observed to have a Q greater than unity. Spectral studies confirm amphibole Fe-rich chlorite mineralogy (Adams & Dentith, 2018);
- Group 3: Handheld instrument values are less than Qmeter data. Samples are observed to have a Q greater than unity. Visible pyrrhotite, shearing or ferruginsed weathering is evident.
- Group 4: Data correlate well. By and large samples are remanently dominant. Spectral studies confirm Mg-rich chlorite with minor or no talc mineralogy (Adams & Dentith, 2018). Apparent porosity sharply decreases when moving from Group 1 to Group 4. Although not presented, preliminary whole-rock geochemical studies show that Group 4 is more silica rich than Group 1, and may therefore explain a decrease in apparent porosity. Furthermore a high magnetic susceptibility and Q greater than unity suggest that these magnetic grains have been better preserved, unlike in Group 1, which are likely to have become finer or partly destroyed due to talc-carbonate alteration.

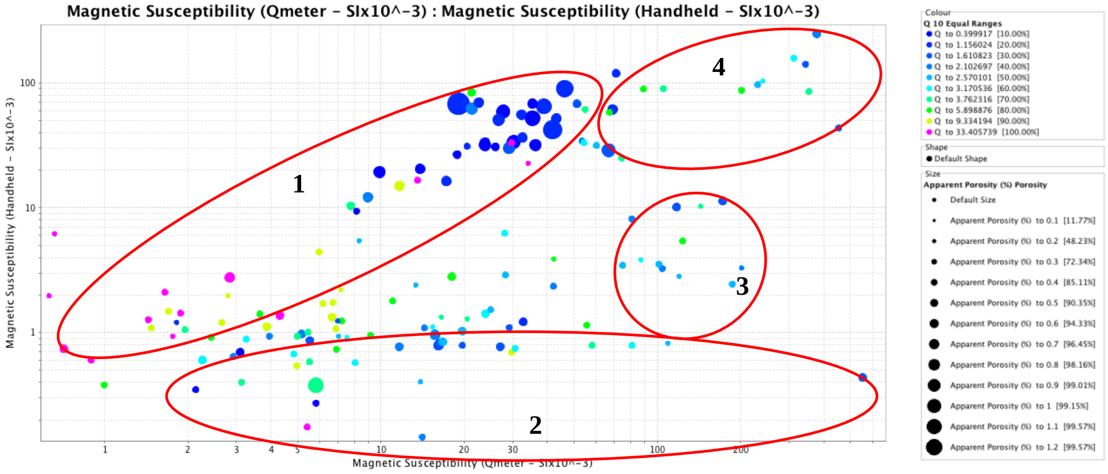

Figure 2: Magnetic susceptibility (handheld) vs. magnetic susceptibility (Qmeter), both in log-scale. Data points are coloured according to Q. Data points are sized according to increasing apparent porosity. Numbered ellipses show distinct populations of data.

CONCLUSIONS

Estimating the dimensions of drill-core to determine volume can lead to extreme error when calculating dry bulk density measurements. Splitting drill-core may propagate a significant amount of error due to cutting procedure. More reliable dry bulk density measurements may be carried out by Archimedes' principle. The reliability of historical dry bulk density data can be ranked by known cutting procedure, including the marking of orientation or bottom-of-hole lines, or known date of core holding device implementation.

The use of handheld inductive susceptibility meters to measure mafic and ultramafic rocks has been investigated. Data show that handheld susceptibility meter values can be significantly in error. These erroneous circumstances are largely attributed to anisotropy.

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